EXPERIMENTAL AND NUMERICAL RESULTS OF THE COUPLED SEAL CAVITY AND MAIN FLOW FOR A LIQUID HYDROGEN ROCKET TURBOPUMP

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STUDY OF THE SSME LH_2 HIGH PRESSURE TURBOPUMP

- Phase 1 and 2 SBIR grant.
- Apply advanced pump and compressor technology to alternate design.
  - good throttleability
  - high efficiency
  - reduced part count
- Investigate front and rear leakage cavities.
  - Coupled cavity-impeller flow character.
  - Effects on thrust balance.

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COMPARISON OF LH2 FIRST-STAGE SSME ROCKET TURBO PUMP IMPELLER WITH ADVANCED TECHNOLOGY IMPELLER

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Conventional LH2 st stage SSME rocket turbopump compared to advanced technology impeller.

increased inlet blade count from 6 to 8

reduced splitter count from 2 rows to 1 row
exit blade count went from 24 to 16

simplified design

MODIFIED CONTINOUS CROSSOVER DESIGN CONFIGURATION

 

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Simpler design

Based on a diffusing vane concept

Substantial reduction in overall diameter with good performance.

Translates to reduced size and weight.

TURBOPUMP TESTED BEHIND THE BILL-OF-MATERIALS SSME LH2 TURBOPUMP INLET ELEMENT

Original SSME LH2 pump and alternative design tested in water rig.

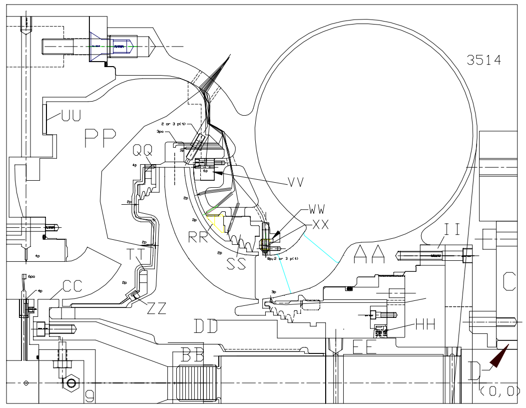
Magnetic bearing rig used to measure radial and axial loads.

Important for thrust measurements for the investigation of the various seal cavity configurations.

Comparison to the CFD predicted axial thrust.

Actual SSME inlet elements used. The inlet pipe and the inlet volute with IGV's

TEST RIG LAYOUT AND MEASUREMENT LOCATIONS



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Point out the various components and seals.

In addition to the axial thrust measurements other instrumentation was included to assess the performance of the stage and investigate the influence of the seal cavities on the performance.

Static pressure taps:

Inlet (hub, tip)

Impeller exit (hub, tip)

Return exit (hub)

3 locations through the front cavity seal

more taps for configuration with bleed at the back face that is not reported here.

Keil probes:

Diffuser throat

Crossover exit.

Previous testing traversed behind the IGV’s of the inlet element to get the flow velocity and angle distribution into the impeller. This information was used for the boundary conditions on the CFD calculations.

CFD MODEL OF THE ALTERNATIVE DESIGN TURBOPUMP

- Model the impeller coupled with the front and rear seal cavities.
- Investigate the flow field inside the seal cavities and compare to test data.
- Investigate the interaction between the seal cavities and the main flow
- Predict axial thrust to compare to test data.

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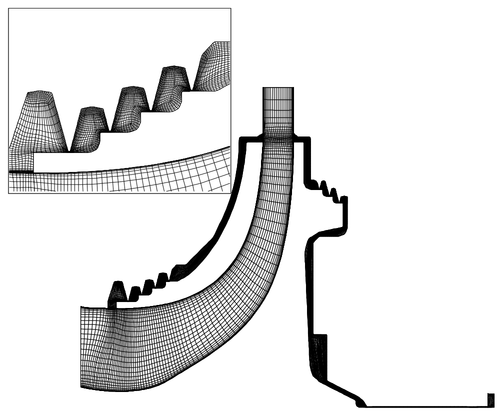
MERIDIONAL VIEW OF MESH WITH FRONT AND BACKFACE CAVITIES



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Structured Multi-block mesh in impeller and seal cavities created with GridPro.

Care was taken to capture important details of the seal cavities.

Mesh clustered in the main flow path to resolve boundary layer.

Boundary Conditions:

1.) Inlet distribution of velocity and flow angle taken from traverses behind the inlet element.

2.) Mass flow was imposed at back face seal cavity to match the measured pressure drop.

FINE/Turbo™ CFD PACKAGE WAS USED FOR THE SIMULATION

- Multi-block structured code
- Central difference discretization
- Time-marching with preconditioning for incompressible flow
- Baldwin-Lomax turbulence model
  - First node spacing y+ ~ 2
  - Reasonable performance in boundary layer dominated flows (main flow path)

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WATER WAS USED FOR THE TEST AND CFD SIMULATION

- Appropriate flow rate and speed was selected for correct similarity scaling between LH_2 and Water.
- Water rig mass flow = 54.3 lbm/s
- Water rig speed = 889 RPM

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TEST DATA PARAMETERS COMPARED TO CFD RESULTS

Parameter	Units	Data	CFD
Mass Flow	lbm/s	54.3	54.4
Wheel Speed	RPM	889	889
Inlet Total Pressure (P00)	psia	22.42	22.43
Impeller Exit Static Pressure (P2)	psia	33.28	32.89
Impeller Exit Total Pressure (P02)	psia	-	42.25
Diffuser Throat Total Pressure (P04)	psia	42.04	-
Shaft Power	hp	5.22	4.82
Total-to-Total Impeller Efficiency (η_{tt})		0.89	0.94
Total-to-Static Impeller Efficiency (η_{ts})		0.47	0.49
Axial Thrust	lbf	768	840
Front Seal Cavity Flow	lbm/s	-	0.50
Rear Seal Cavity Flow	lbm/s	-	0.33

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3.5% low in pressure rise prediction

2 points high in static to static efficiency

5 points high in total-to-total efficiency estimate - but we don't have a good number for the the impeller exit total pressure

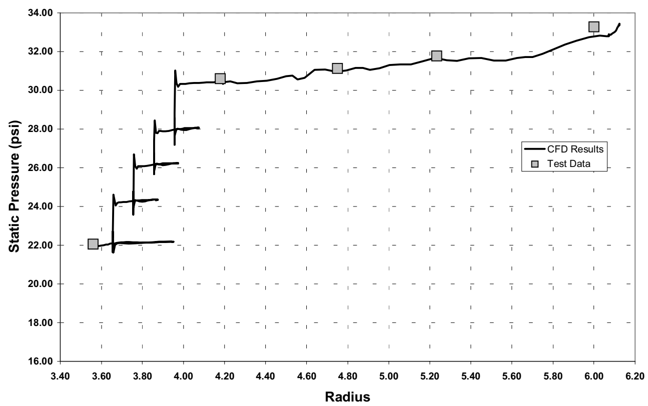
7.5% low in shaft power

didn't get the skin friction right on the seal cavity walls

Axial thrust is high by about 9%

Predicted seal cavity mass flows are on the order (percentage wise) of what was assumed in the SSME engine.

COMPARISON OF CFD PREDICITONS TO TEST DATA OF STATIC PRESSURE ALONG FRONT SEAL CAVITY OUTER WALL



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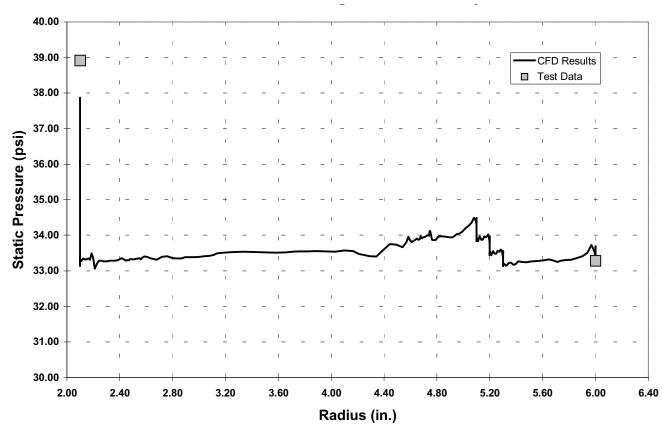
Generally good agreement between test data and CFD results.

Clearly see the drop in pressure across the seal teeth.

Predictions are a little bit low in static pressure towards the tip. If we integrate the difference in static pressure in the tip region we come up with a value of about 19 pounds force due to the difference. This is about 2.5% of the higher predicted thrust value

The other 6 or 7% difference has to be tied up in the rear seal cavity predicted pressure distribution.

COMPARISON OF CFD PREDICTIONS TO TEST DATA OF STATIC PRESSURE ALONG REAR SEAL CAVITY WALL



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Mass flow adjusted to try and match the pressure drop.

Unfortunate that we didn’t have internal static taps to see which parts of the backface, if any, that we are getting right

Significant influence of the damper seal on the pressure drop and mass flow through the cavity. Small variations in the test build could have large impact.

See the gradual pumping of the fluid up to the labyrinth seals.

Pressure distribution is highly dependent on the mass flow. Implies that we don’t have the right mass flow imposed through the back face seal. Should run this coupled to the crossover return.

STREAMLINES IN MAIN FLOW PATH AND THE FRONT AND REAR SEAL CAVITIES

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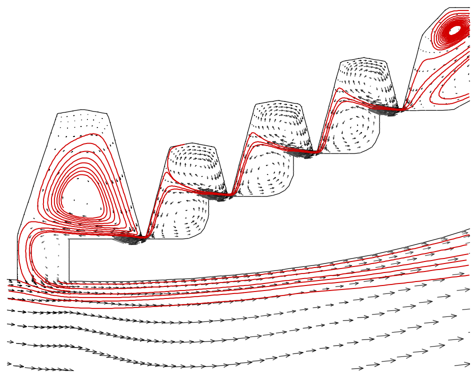
VELOCITY VECTORS AND STREAMLINES SHOW THE DETAILS OF THE FLOW IN THE FRONT CAVITY LABYRINTH SEALS



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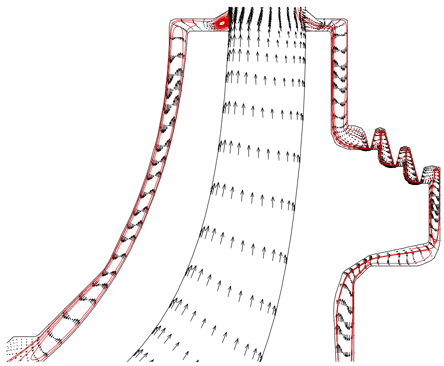
VELOCITY VECTORS AND STREAMLINES - DETAILS OF FLOW IN THE FRONT SEAL CAVITY AND REAR CAVITY LABY SEALS



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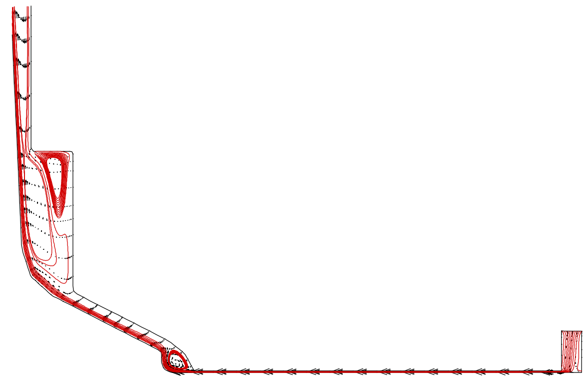
VELOCITY VECTORS AND STREALINES SHOW DETAILS OF FLOW IN THE BACK CAVITY NEAR DAMPER SEAL



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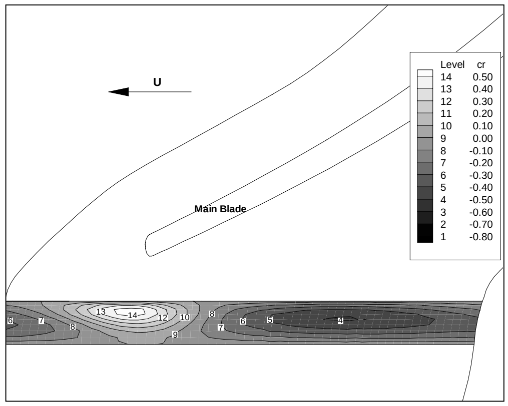
RADIAL COMPONENT OF VELOCITY CONTOURS AT LOCATION OF SEAL CAVITY INJECTION INTO IMPELLER EYE



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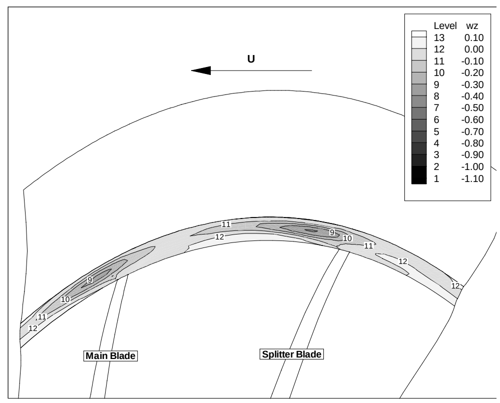
AXIAL COMPONENT OF VELOICTY CONTOURS AT LOCATION OF SEAL CAVITY INJECTION FROM IMPELLER EXIT



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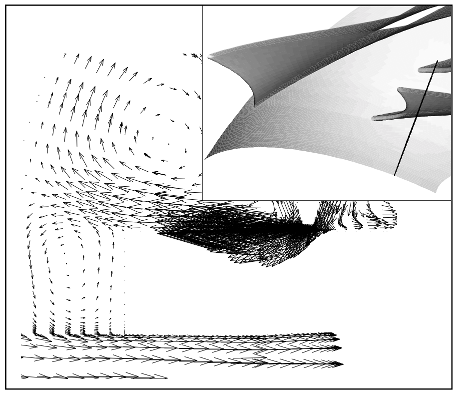
VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION (θ = 0.0°)



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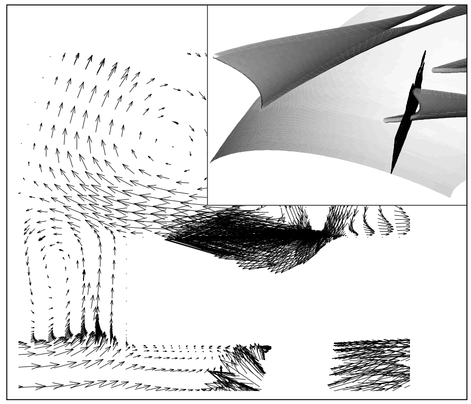
VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION (θ = 5.0°)



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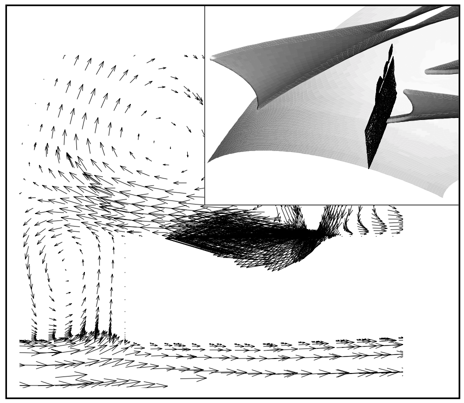
VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION (θ = 10.0°)



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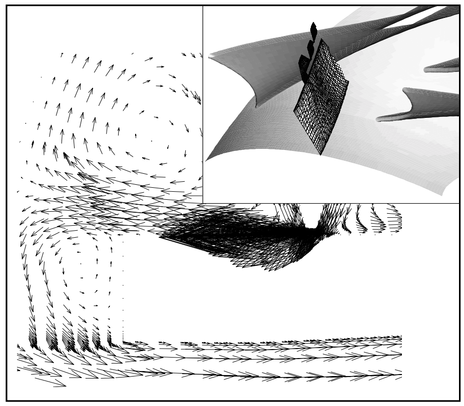
VELOCITY VECTORS AT IMPELLER EYE INJECTION LOCATION (θ = 25.0°)



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CONCLUSIONS

- Generally good agreement between CFD predictions and test data.
- Axial thrust prediction was slightly high.
- CFD model that includes seal cavities can be used for good axial thrust predictions.
- Unexpected reverse flow into and out of the seal cavity identified which could impact performance.

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